New Dwarfs from the PSS-II: A Test of BGF†

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"The sciences do not try to explain, they hardly even try to interpret, they mainly make models. By a model is meant a mathematical construct which, with the addition of certain verbal interpretations, describes observed phenomena. The justification of such a mathematical construct is solely and precisely that it is expected to work." - John von Neumann

1. Introduction

Dwarf galaxies have received a great deal of observational attention in the last decade for two reasons. The first is that their intrinsic properties provide insight into galaxy formation because dwarfs have a simpler past history compared to star-forming giant galaxies. Studying the range of galaxy types from dwarfs to giants is also a key test to galaxy evolution models. The second reason has arisen in recent years as investigations into dark matter have questioned the basic premise that light traces the mass in large scale structure and that dwarfs, or low mass galaxies, may better sample the distribution of mass in the Universe.

The hypothesis that bright, or high mass, galaxies do not trace the true mass distribution of the Universe has come about due to the failure of various cosmological models to correctly predict the amount of large scale structure (voids and walls), or the observed peculiar velocities, Parallel to these efforts was the suggestion from grand unified theory (GUT) of new types of stable particles with non-zero mass that interact only weakly with baryons (Turner 1987). The introduction of what has been called cold dark matter (CDM) resolves the following cosmological problems: 1) it allows Ω_o=1 without violating the baryon density (Ω_b=0.2) set by primordial nucleosynthesis, 2) CDM allows growth of present day large scale structure from fluctuations currently measured by COBE in the cosmic microwave background (CMB), since the CMB only responds to baryons, 3) CDM can be more smoothly distributed than baryons such that dynamical estimates for Ω_o are too low, 4) it resolves conflicts between cluster models and the galaxy distribution since galaxies do not trace the mass and 5) weak interactions form the basis to segregate baryonic and non-baryonic matter to form dark halos (see Oemler 1989 for a review). The only missing piece is a mechanism to segregate CDM from baryonic matter, On small scales, such as galaxy halos, dissipation is sufficient, but on large scales the mechanism remains a mystery. This has led to the speculation that an inefficiency in galaxy formation produces a bias in the distribution of bright galaxies such that they only trace the peaks of the mass distribution. The theoretical justification for biasing arises from the assumptions that if galaxies form from high σ fluctuations and if those fluctuations are superimposed on uncorrelated, random, larger-scale fluctuations of small amplitude, then galaxies will be more clustered than the underlying matter distribution (Kaiser 1984).

The theoretical community has also found support for a biased galaxy formation scheme in the many selection effects inherent in galaxy catalogs that would maximize a biased interpretation observational results such as the autocorrelation function for galaxies. For example, there is a clear surface brightness bias in glaxy catalogs to select against objects with central surface brightnesses near the natural sky brightness. Theory predicts that low surface brightness (LSB) galaxies are the result of lower amplitude fluctuations and that redshift surveys without a complete sample of LSB objects are biased (Me, McGaugh and Bothun 1994). Although not all LSB galaxies are dwarfs (Bothun *et al.* 1987) nor are all dwarfs of a LSB nature, there is a tendency for HI-rich dwarfs to have central surface brightnesses

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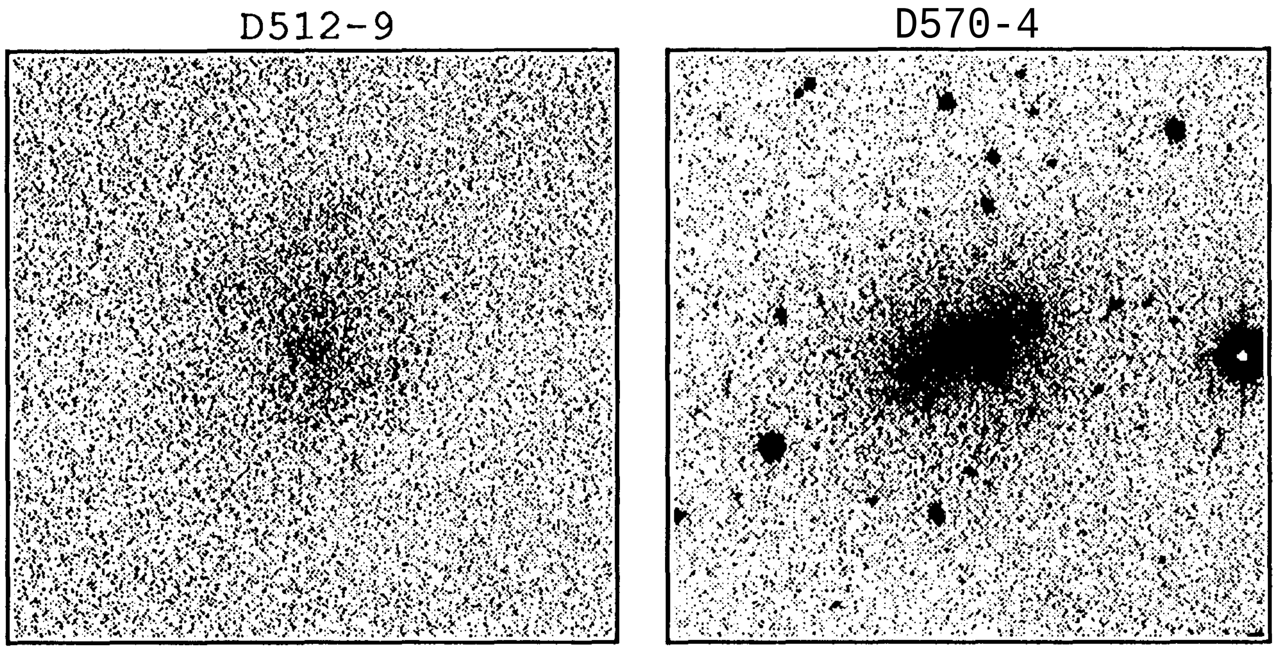

Figure 1, Two dwarf galaxies from our sample: D512-9 is an example of a low surface brightness dwarf. Note its irregular shape with a lack of smoothness, which gives it a Im classification. Its central surface brightness is 24.0 B mag arcsecs^{-2}. It has an absolute mag of -17.5 and an HI mass of 1.5 x $10^9 M_0$. The image is 72 arcsecs to a side which corresponds to 10 kpc at the distance of D512-9. D570-4 is an example of a higher surface brightness dwarf with a μ_o = 23,1 B mag arcsec^{-2}. Its absolute mag is –13.8 with a total HI mass of 4.8 x $10^7 M_0$. The image is 122 arcsecs across corresponding to 5 kpc at the distance of D570-4.

below *2311* mag arcsec^{-2}. In addition, catalogs, such as the UGC, that have deeper surface brightness limits will fail to find small dwarf galaxies at useful distances to study large scale structure, since they quickly fall below the angular size limits outside of 1000 km sec^{-1}. Catalogs specific to dwarf galaxies have concentrated on surveying rich clusters, such as Virgo or Fornax (Binggeli, Sandage and Tammann 1984, Caldwell and Bothun 1987), where the number density of dwarfs is high, but these catalogs are also not useful in studying the large scale distribution of dwarfs. The purpose of our project is to overcome both of these deficiencies in galaxy catalogs by attempting to recover field LSB dwarf galaxies to sample their spatial distribution out to cosmologically meaningful distances.

Our original project using the new Sky Survey (POSS-II) plates was published in Eder *et al. 1989*. That project used 14 pre-production J plates to find 102 dwarfs around the void centered at 0^h45^m, *3500* km sec^{-1}. The distribution of bright and faint galaxies was found to be identical in that study, and the void was as well defined by dwarf galaxies, Our new endeavor has two purposes. The first is to extend our search to a larger area of the spring sky with increased velocity depth. The second is to determine the optical and HI properties of the dwarfs to define the meaning of low mass versus high mass galaxies as a more exact test of BGF. We have also concentrated on locating LSB dwarfs of small angular size that would be missing from a surface brightness limited catalog, such as the CGCG, or an angular limited catalog with high size limits, such as the UGC. All distance related values in this paper use values of H_o = 85 km sec^{-1} Mpc^{-1}, Ω_o = 0,2 and a Virgo infall of 300 km sec^{-1}.

II. POSS-II Dwarf Galaxies

a) Sample selection

The plate material for the selection of dwarf galaxies comes from 60 min A or B grade J (4900Å) plates of the Second Palomar Sky Survey currently underway on the 48-inch Oschin Schmidt telescope on Palomar Mountain. The search region was between RA's of 7^h to 16^h and declinations of 10° to

25°. The new survey has a demonstrated depth of 1 mag arcsec^{-2} deeper than the old Sky Survey and is particularly suited for searches of LSB objects (Schombert and Bothun 1988). Our search was visual using a low power eyepiece by only one of us (JS) and a morphological criterion was applied to isolate dwarf candidates. This criterion was, primarily, to find objects with irregular appearance typified by the extended Hubble sequence as outlined by Sandage and Binggeli 1984. As shown in Schombert *et al.* *(1992)*, a catalog of LSB galaxies is composed of three classes; 1) dwarfs, 2) LSB disks (quiescent counterparts of star-forming spirals) and 3) Malin objects (supergiant LSB disks). To avoid the later two categories in our sample, wc concentrated our follow-up observations on objects that appeared to be Sm, Im, Irr, BCD, dI or dE, with a special emphasis on LSB objects and objects with small (down to 10 arcsecs) angular size. For comparison, the UGC, with its one arcmin size limit, would catalog objects 4 kpc in diameter out to only 1200 km sec^{-1}. Each object was assigned a quality index to rate its probability of being a true dwarf with a velocity between 500 and 10,000 km sec^{-1}. Our visual search produced 310 candidates off of 33 plates (1400 square degrees). When combined with the LSB catalog of Schombert *et al.* (1992), a final list of 350 objects was tallied. Two objects arc shown in Figure 1, displaying the range in surface brightness and absolute luminosity that the sample entailed.

b) Optical and HI Observations

From our initial sample of 350 objects, 230 with high quality indices were observed on the Arecibo 300-ft telescope at 21-cm out to a velocity of 10,000 km sec^{-1}. Of the galaxies observed, 134 were detected. The objects not detected were probably background LSB spirals (with spiral patterns that were not visible on the plates) or gas-poor dwarfs (dE's). The loss of gas-poor dwarfs from the sample is unfortunate since the distribution of dE's outside of a cluster environment is not known or even if a true dE exists independent of a high local density or nearby companion (Binggeli, Tarenghi and Sandage 1990). However, it is not critical to our attempt to locate low mass test particles at cosmologically interesting distances.

The distribution of HI masses is shown in Figure 2. Also shown in Figure 2 is the distribution of HI masses from the Schneider *et al.* study of UGC dwarfs and the general distribution of HI masses for all UGC galaxies regardless of morphological type (all corrected to H_o = 85). Our sample of morphologically selected objects matches closely the same range of HI masses as the UGC dwarfs. We have a few extra high mass LSB disk galaxies (Sm, Sc) compared to the UGC dwarf sample and wc have relatively more galaxies with HI masses near $10^8 M_\odot$. The extra number of higher mass systems is duc to the ambiguous classification of LSB objects with disks. However, if we removed all objects with possible disks as indicating higher mass then wc would have missed several true dwarf spirals (see below). Otherwise, our sample falls at the very low end of the general distribution of HI mass from the entire UGC, reinforcing our belief that our selection criteria identifies true dwarfs from the field, at least in terms of HI mass.

Of the detections, 110 were imaged on the MDM Observatory 2.4m telescope at V and I. Wc had three goals to accomplish via imaging. They are: to provide 1) an absolute magnitude for each dwarf, 2) a scale length and central surface brightness from surface photometry fits to the 2D images and 3) colors to probe the stellar content of the dwarfs. Our optical results arc summarized in Figure 3, where only objects with HI masses less than $10^9 M_\odot$ arc plotted. Our absolute V luminosities arc less than – 17, which means that all of our objects are fainter than the brightest dwarfs in the Virgo cluster (Sandage, Binggeli and Tammann 1985). Our central surface brightnesses (based on exponential fits to the I band profiles) range from 21 to 23 I mag arcsec^{-2} (given the mean colors, this is roughly 22 to 24 B mag arcsec^{-2} compared to the canonical value of 21.5 for a disk galaxy) and typical scale lengths arc 0.2 to 1.5 kpc (compared to 2 to 3 kpc for disk galaxies). The mean $V-I$ color is quite blue at 0.7 (for comparison, the typical color of HSB Sc to Im galaxies from the sample of Corwin 1993) is $V-I$=1.1), although it is now common to find bluer colors with decreasing surface brightness (see below). Many of the galaxies have lumpy, fragmented appearances, but these lumps have the same colors as the envelopes and do not appear to be star formation sites or young clusters, but rather transient concentrations of stars duc to orbit coincidence.

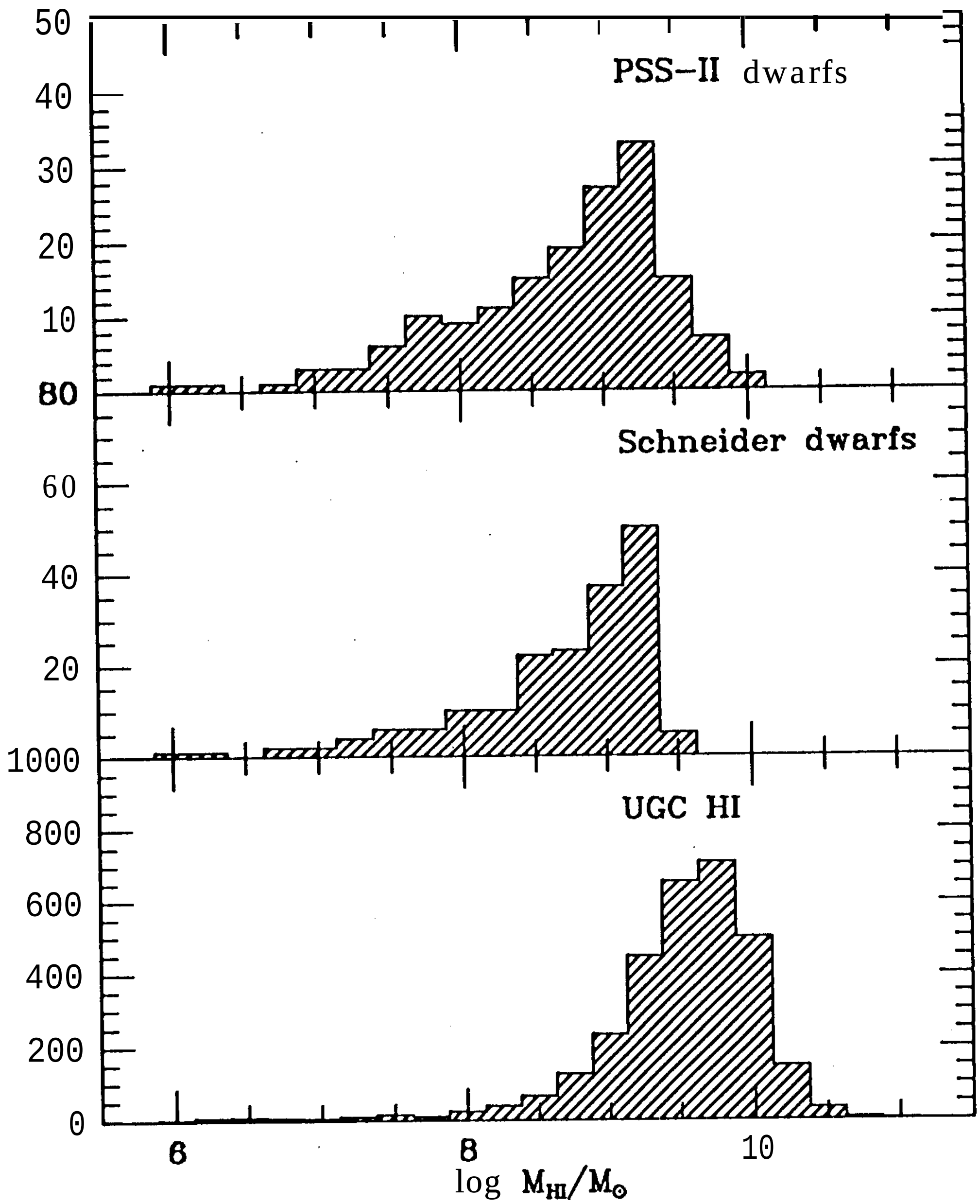

Figure 2. The distribution of HI mass for the }'SS-11 sample, Schneider *et* al. (1990) dwarfs, and the UGC catalog HI detections taken from Huchtmeier and Richter (1983). All distances calculated using H_o = 85 km See 1 Mpc^{-1}, Ω_o = 0.2 and a Virgo infall of 300 km sec^{-1}. Note that the distribution of PSS-II dwarfs is similar to the Schneider *et* al. sample selected from the UGC dwarfs, and that both dwarf samples define the low mass tail of the entire UGC catalog (i.e. selecting galaxies to be dwarfs by morphology automatically selects low HI mass objects).

Structurally, most of the galaxies in this sample were characterized by exponentially declining light profiles with little to no color gradient. A few objects had faint bulges (see the section on dwarf spirals below) or box-shaped profiles, but, in general, the sample had the structure as that exhibited by cluster dwarfs (Bothun, Impey and Malin 1991). In early work on LSB galaxies, an LSB appearance was attributed to stellar population differences; that is, the primary population in LSB galaxies was thought to be an old red stellar component. However, the blue colors wc observe imply that LSB nature of these dwarfs represents a real decrease in volume mass density (i.e. LSB dwarfs have fewer stars pcr pc^3 then their HSB counterparts). The surface brightnesses translate into 201.0 pcr pc^{-2}, assuming a

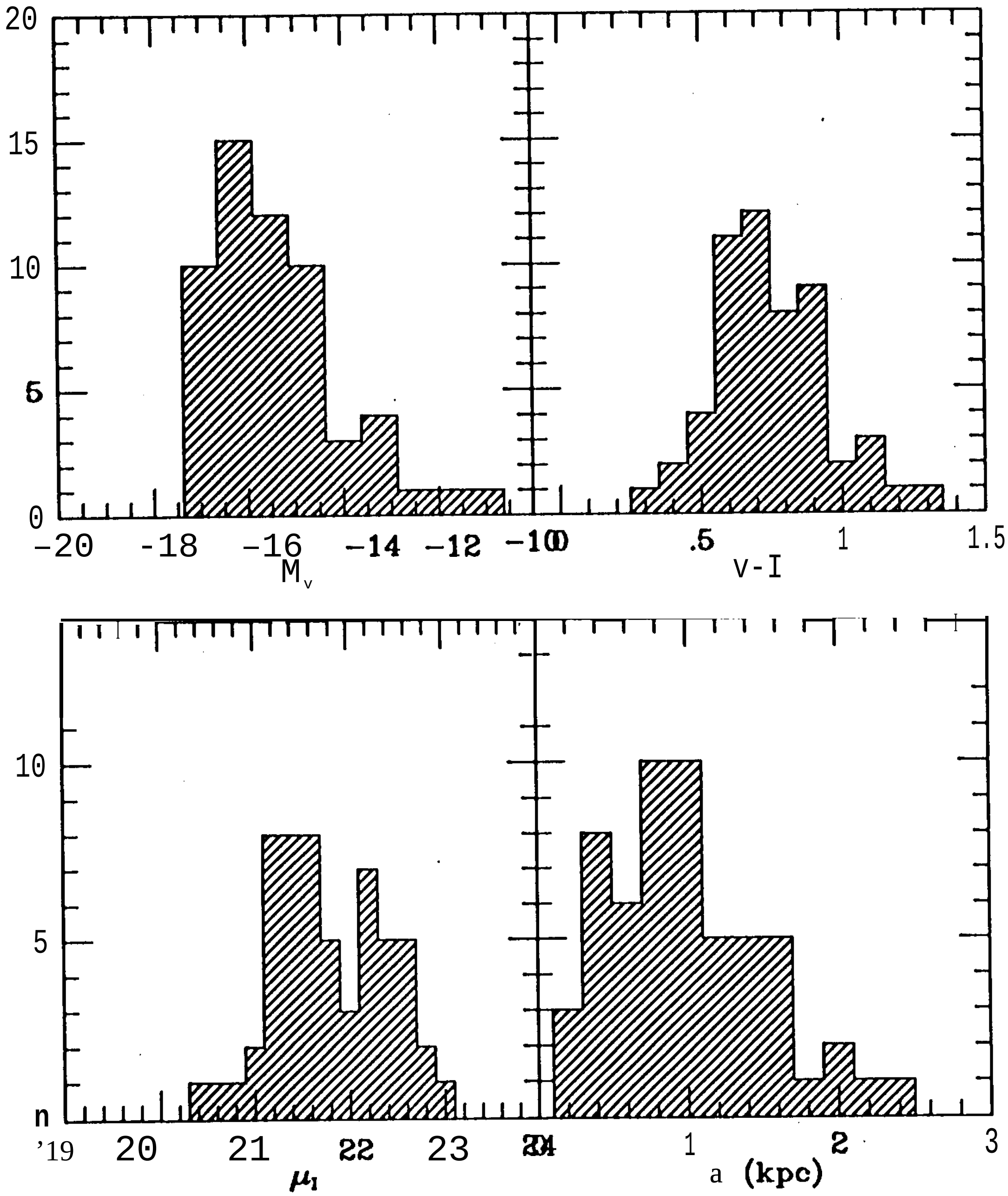

Figure 3. The optical properties of our new dwarf sample displayed as absolute V mag (upper left), mean $V-I$ color (upper right), central surface brightness at I (lower left) and scale length in kpc from exponential fits (lower right). By any definition the morphologically selection criteria produced a set of faint, small, blue, LSB dwarfs. Note the $V-I$ colors are quite blue compared to the typical HSB Sc color of 1.1.

standard IMF, emphasizing these galaxies' probable origin in low σ fluctuations in the early Universe. We feel the large fraction of LSB dwarfs versus HSB dwarfs found in this survey is representative of the true distribution in surface brightness of dwarfs and not a selection effect, and that previous catalogs, such as Zwicky's compact galaxy catalog, Were biased to bright, star-forming Irr's.

c) Star Formation History

The current star formation rate in dwarfs can span the same range of activity as the giant versions of Hubble types. On the inactive end are the dE's with their symmetric, metal-poor appearance that suggests an early formation epoch where galactic winds halted star formation after less than 1 Gyr.

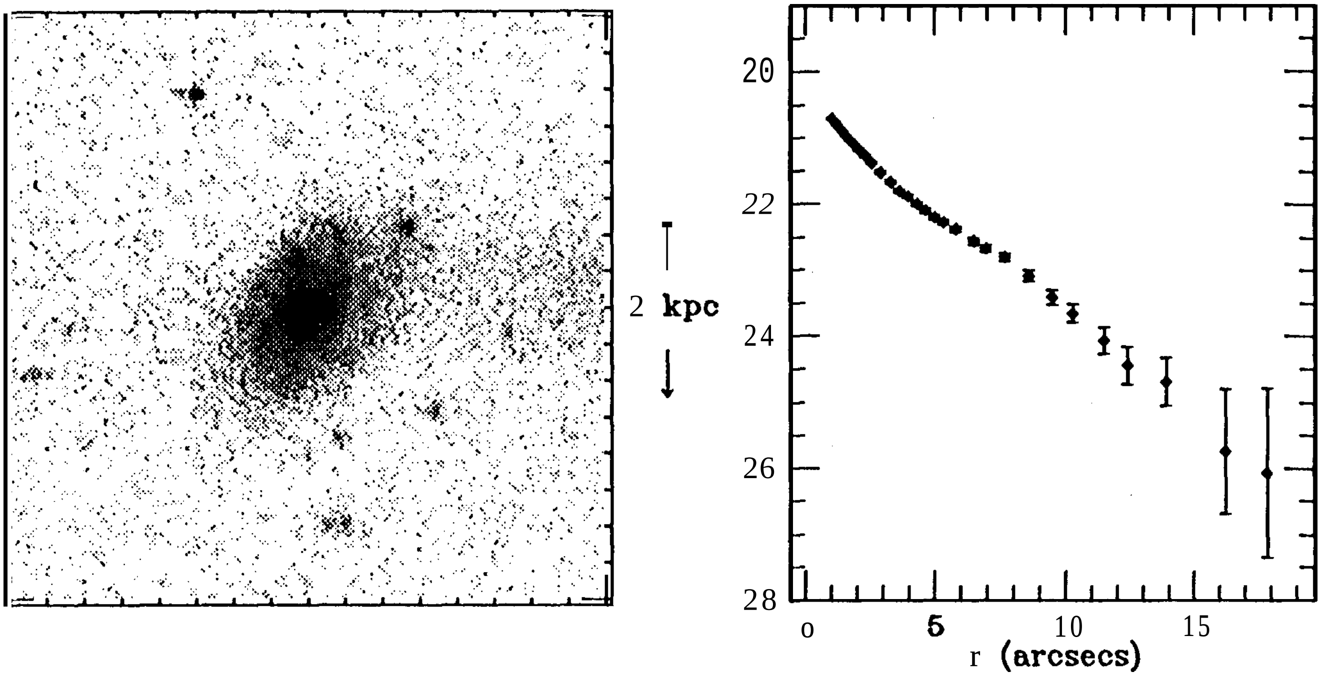

Figure 4. One of the dwarf spirals detected in our sample. D565-7 is located at a velocity of 1242 km See^{-1} with a HI mass of 7.6 x 10^7A J_0 and a line width of 108 km sec^{-1}. Its absolute V mag is – 14.8. Its surface brightness profile is shown to the right with a disk and faint bulge component visible.

On the other extreme are the star-forming Irr's and blue compact dwarfs (BCD's) which appear, as a class, to be currently undergoing strong star formation events encompassing a significant fraction of their current gas supply. The LSB dwarfs in our sample primarily fall in the late-type classes of Im or d] with little or no evidence of recent star formation and with large gas to light ratios.

The contradiction of blue $V - I$ colors, bluer than star-forming Se's, has become quite common in optical studies of LSB galaxies (Schombert *et al.* 1992, McGaugh and Bothun 1994). The original idea that LSB objects are the result of fading of old stellar populations has been shown many times to be incorrect. Nor arc these systems unusually blue due to a peculiar IMF or exotic stellar populations (Schombert *et al.* 1990). While LSB galaxies arc low in global metallicity, their $B - V$ colors arc too blue relative to $V - I$ *even* as compared to low metallicity globular clusters (McGaugh and Bothun 1994). McGaugh and Bothun (1994) conclude that their LSB sample of galaxies, although not composed solely of dwarfs, have very blue $B - V$ and $V - I$ colors duc to an underpopulated giant branch from sporadic star formation episodes and a late formation epoch of only 5 Gyrs ago. Although it has been known for over 20 years that high surface brightness, star-forming dwarfs arc not young galaxies due to the existence of an underlying red population (Searle, Sargent and Bagnuolo 1973), LSB dwarfs, by contrast, arc dominated by a stellar population which display all the properties of a young 5 Gyr population. This implies that these galaxies have a delayed formation timescale as onc would expect from galaxies formed from low σ fluctuations in the early Universe.

d) Dwarf Spirals

In their survey of the Virgo cluster, Sandage and Binggeli (1984) found no evidence for dwarf galaxies of the Hubble type Sa to Sc although there are dwarf SO's). Their criteria were based on luminosity in the sense that no object in the VCC catalog with a measured redshift displayed spiral structure below $M_B = -17$. This is a relevant observation with respect to the theory of disk formation and stability for, although all low luminosity galaxies have exponential profiles (Binggeli, Sandage and Tarenghi 1984), this dots not necessarily imply rotationally supported structure. The lack of dwarf spirals in current

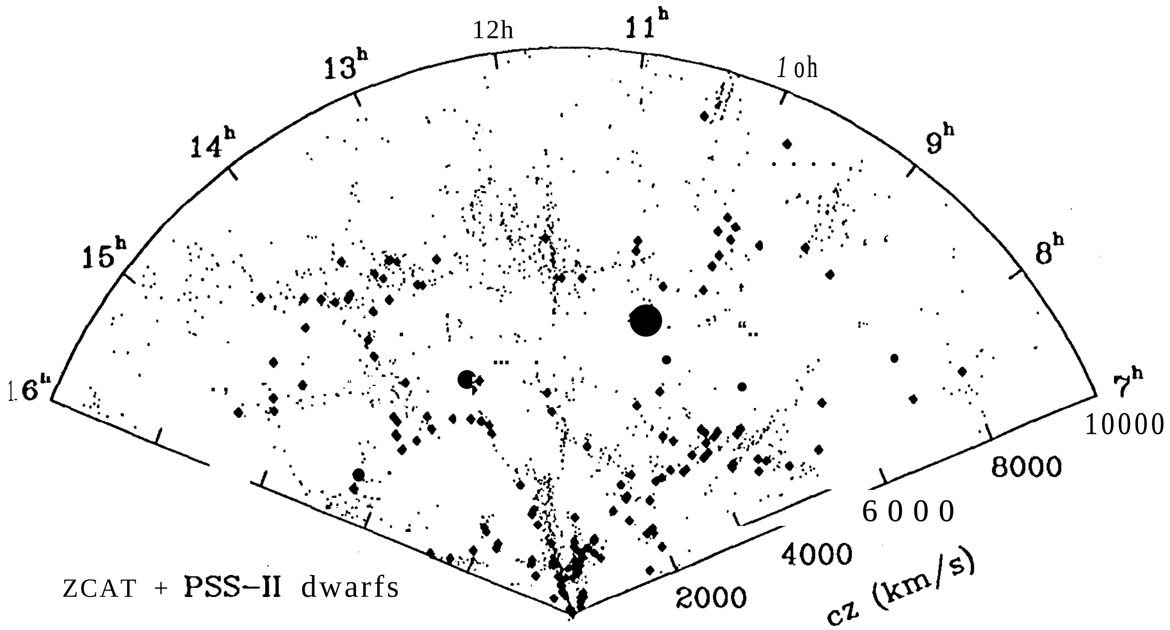

Figure 5. Our main result is summarized by this wedge diagram of the dwarfs in our new sample (solid diamonds) and the bright, high mass galaxies from the CfA survey (dots). The LSB dwarfs and bright galaxies map the same large scale structure in a direct contradiction of the prediction of biased galaxy formation.

galaxy catalogs may simply reflect the limitations of magnitude, surface brightness, or angular size for those catalogs. The deepest catalogs for dwarfs have emphasized nearby rich clusters and groups, such as Virgo and Fornax, where a dense environment may be fatal to the survival of a dwarf spiral. In the field, the CGCG is complete in magnitude to small angular size, but is lacking many LSB systems. The UGC is more complete in surface brightness, but has a lower angular size limit of 1 arcmin. This angular limit corresponds to over 3.5 kpc at 1000 km See–l and, thus, the UGC may not cover enough volume to have cataloged a dwarf spiral. in fact, the smallest spiral in the UGC is 4.6 kpc in diameter (UGC 1234C) Our survey limits allow the detection of 3 kpc, 1,S13 objects out to 4000 km See^{-1}, 64 times the volumc of the UGC.

Duc to the low surface brightness nature of our sample, classification to the extended Hubble sequence was subjective at best. Several objects displayed little structure on the plate material, but deep CCD imaging revealed greater contrast and more structure. Thirteen of our galaxies with metric diameters less than 3 kpc display flocculent spiral structure and over half of those have small bulges. 'The visual impression one gets from these dwarf spirals is an M33-like galaxy without the regions of star formation. Onc example, 1>565-7, is shown in Figure 4. Its total mag is –14.8, much less than LIST'S dwarf limit. This spiral pattern is very low in surface brightness and, in most cases, was not visible on this original plate material. We conclude that these arc real dwarf spirals and that the Hubble sequence is complete from giants to dwarfs for all major galaxy t ypes.

III Biased Galaxy Formation

The key test on the hypothesis of biased galaxy formation is not the relative distribution of faint to bright galaxies, but galaxies that formed fom high σ fluctuations versus those that formed from low amplitude fluctuations. This, is in effect, is a comparison of high versus low mass galaxies, or giant versus dwarf, or LSB versus HSB galaxies, based on our understanding of the process of galaxy formation. In addition, our analysis of the star formation history indicates that LSB dwarfs arc the result of inefficient galaxy formation, which again reinforces our belief that they arc good test particles of BGF. Since some parameters, such as total mass, arc difficult to determine, wc have defined our dwarfs by four criteria: 1) luminosity, 2) size, 3) line width, and 4) HI mass. Our main conclusion can bc summarized by Figure 5 where wc plot the distribution of our dwarfs (selected by luminosity for this plot) and bright galaxies from the CfA redshift survey. It is obvious from this figure that the dwarfs map out exactly the same large scale structure as bright galaxies. This is confirmed by a nearest neighbor test and cross-correlation function. The same distribution is found if the sample is selected by size or HI mass or HI line width. We find no evidence that LSB dwarfs are clustered differently from other kinds of galaxies. This is in agreement with our original work (Eder *et al.* 1989), the dwarf study by Binggeli, Tarenghi and Sandage (1990), and the study on the clustering of LSB disk galaxies by Mo, McGaugh and Bothun (1994). We conclude that if CDM is to continue to bc used in our interpretation of large scale structure, then a different mechanism other than biased galaxy formation must bc found to segregate light and matter.

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